Fluctuations of Mid-to-High Frequency Acoustic Waves in Shallow Water

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LONG-TERM GOALS

The long-term goal of this project is to obtain quantitative understanding of the physical mechanisms governing broadband (50 Hz to 50 kHz) acoustic propagation, reflection, refraction, and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

OBJECTIVES

The scientific objective of this research is to understand acoustic wave propagation in a dynamic environment in two frequency bands: Low (50 Hz to 500 Hz) and Mid-to-High (500 Hz to 25 kHz). The goal for the low frequency band is to assess the effect of internal waves on acoustic wave propagation, with an emphasis on the mechanisms that cause acoustic temporal and spatial intensity fluctuations. The goal for the mid-to-high frequency band is to assess the effects of water column and sea surface variability, as well as source/receiver motion on acoustic wave propagation for underwater acoustic communications and tomography applications.

APPROACH

We have initiated numerical modeling, with calibration based on theory and data comparison. Studies in the low frequency band have utilized data from the SW06 experiment collected in summer 2006 with both stationary and moving sources [1]. Moving source transmissions provide a unique opportunity to investigate different mechanisms that can explain acoustic intensity fluctuations in the presence of internal waves. A mode filtering technique was applied to the data to gain a better understanding of separate modal correlations. Studies in the mid-to-high frequency band have utilized data collected during the KAM08 experiment [2]. The effects of a moving source, as well as those of sea surface and water column variability, on acoustic wave propagation have been investigated in order to understand the physics of the waveguide in 5-30 kHz frequency band.

WORK COMPLETED

1) *Low Frequency Acoustic Wave Propagation.* Progress has been made in understanding the three-dimensional (3-D) effect of low frequency propagation in shallow water in the presence of internal

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14. ABSTRACT
The long-term goal of this project is to obtain quantitative understanding of the physical mechanisms governing broadband (50 Hz to 50 kHz) acoustic propagation, reflection, refraction, and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

15. SUBJECT TERMS

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waves [1, 3-7]. The effects due to horizontal refraction are separate from those due to mode coupling and adiabatic regimes. Our theoretical model [4] has been confirmed through comparison with data from SW06 [1].

2) *High Frequency Acoustic Wave Propagation.* Both stationary and moving source data in KAM08 have been analyzed to assess the effects of source movement and environment variability on the acoustic wave propagation for acoustic communications. As part of the modeling effort, a more realistic 2-D surface wave representation has been developed and applied for the directional waverider buoy data from KAM08. This rough surface model has been integrated into the existing 2-D ray-based and parabolic equation (PE) models to simulate the effects of surface roughness [8].

3) *Instrumentation.* The sensor and electronic components for the University of Delaware payload module, developed for the Gavia AUV, have progressed to the level where initial field testing and sensor calibrations are possible. The module has passed testing and analysis procedures in a laboratory environment (through both independent component and assembled unit analysis) using signal processing and electronics monitoring hardware.

RESULTS

A. Low Frequency Acoustic Wave Propagation in the Presence of Shallow Water Internal Waves

In previous studies, we proposed that the mechanism of acoustic wave propagation through internal waves is governed by the direction of the acoustic propagation track between the source and receiver with respect to internal wave fronts [4]. The mechanism changes from adiabatic to mode coupling or horizontal refraction depending on the angle between the acoustic track and the advancing internal wave front. Based on this theory, a source moving in a semi-circle around a fixed receiver through an advancing internal wave would produce results to show this effect. Such an experiment was designed and conducted in summer 2006 (SW06 Experiment). The data obtained during SW06 are being analyzed for comparison with the theory. An example is shown below.

On August 17, 2006, at about 18:00 GMT, the R/V Sharp from the University of Delaware and the R/V Oceanus from Woods Hole Oceanographic Institution (WHOI) observed the origination of an internal solitary wave (ISW) near the shelf break. This event was named Event 50 on R/V Sharp and Rosey on R/V Oceanus. The positions of the moving source (R/V Sharp), stationary source (NRL 300), and WHOI vertical line array (VLA) receiver during this experiment are shown in Fig. 1. The R/V Sharp's track was semi circular, centered at VLA receiver with the ship being positioned on the trough of the leading ISW front and moving with the advancing front. Chirp signals were transmitted in five transmission zones from a J15 source on the R/V Sharp (Fig. 1). Radar images on the R/V Sharp and the R/V Oceanus tracked the internal wave propagating through the experiment site. Previous results from the stationary source (NRL300) have shown that horizontal refraction occurs at small angles [1].

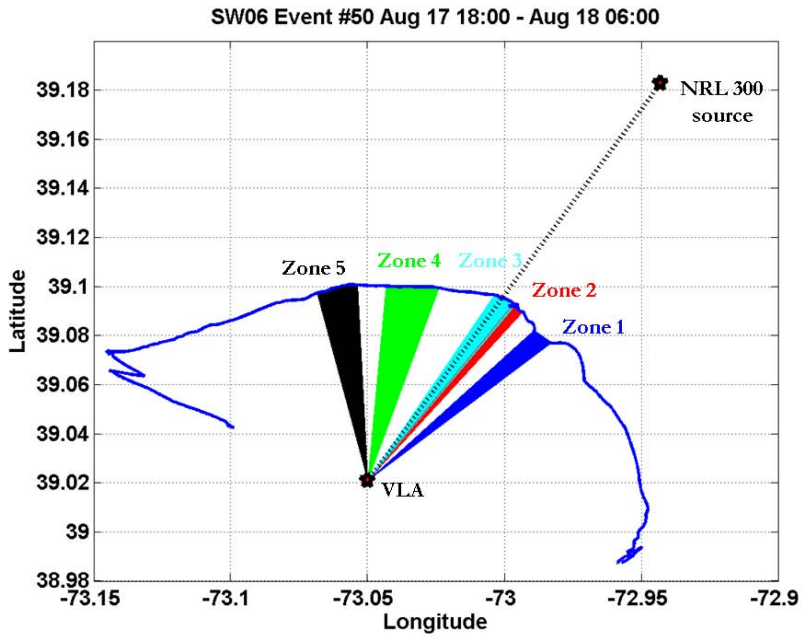

Figure 1: Positions of the fixed (NRL 300) and moving (R/V Sharp) acoustic sources, WHOI vertical line array (VLA) receiver, and 5 zones of transmissions.

In Fig. 2, the top panels show the received acoustic signal on the shark VLA, while the bottom panels show the depth integrated intensity $I = \frac{1}{\rho c}\int_0^H \int_\tau^{\tau+\Delta\tau} p^2(z,T,t)dt\ dz$ where $\Delta\tau$ is pulse length, H is water depth, p is acoustic pressure, ρ is water density, and c is sound speed. At about 21:15 GMT (Zone 1), a small part of an ISW package reached the receiver while the major part was still outside the acoustic track between the moving source R/V Sharp and the VLA. From 21:41 GMT, the ISW started to intersect the acoustic track. Intensity fluctuations of about 7 dB were observed on the VLA in Zones 2, 3, and 4. In agreement with our proposed theory, the acoustic wave propagation mechanism showed horizontal focusing. When the source (R/V Sharp) traveled into the large angle region (Zone 5), only weak (~2dB) fluctuations were recorded on the receiver, which confirmed that horizontal refraction was no longer the dominant mechanism. Mode filtering was applied to the moving source data to calculate the modal correlation coefficients. ISW caused modal correlation values to drop and oscillate close to the frequency of the internal wave (Fig. 3). When the ISW intersects the acoustic track, greater angles between the internal wave fronts and the track correspond to further reductions in the oscillation amplitude of modal correlations. These results are being used to develop temporal and spatial coherence functions for the acoustic propagation through internal waves in shallow water.

Moving source transmissions during the SW06 experiment provided a unique opportunity to study the propagation mechanism as acoustic signals traveled through an internal wave train, especially its relationship with the angle between the ISW wave front and the direction of the acoustic track. Analysis of acoustic data shows that horizontal refraction causes significant acoustic intensity fluctuations. Furthermore, data from Event 50 shows that it can only occur in a limited angular sector. Future work will include a full 3-D PE model to quantitatively analyze the focusing/defocusing and the transition between different propagating mechanisms.

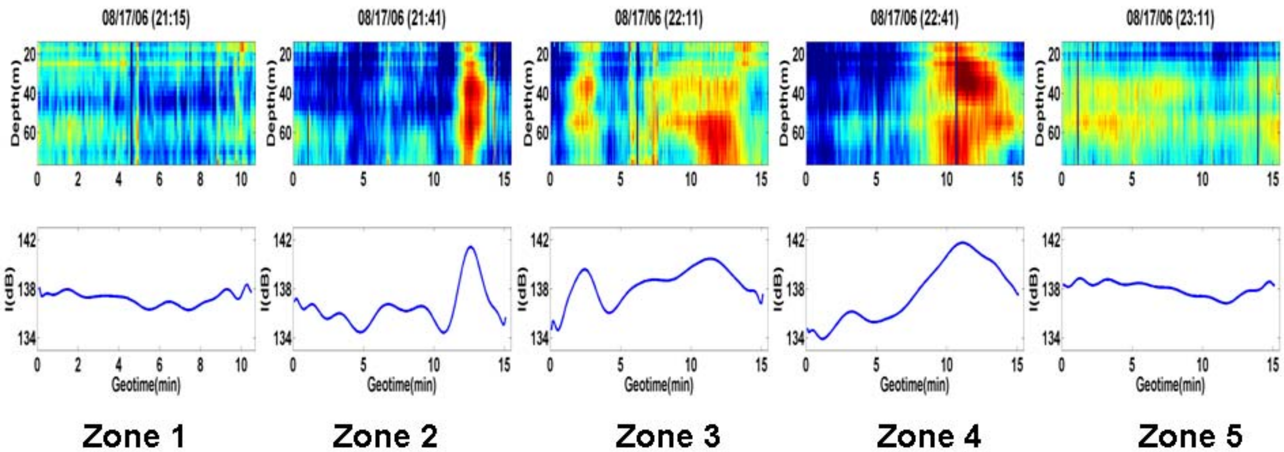

Figure 2: Top panels: Received acoustic signal on WHOI vertical linear array (VLA) in transmission Zone 1 to Zone 5. Bottom panels: Depth integrated intensities in transmission Zone 1 to Zone 5. Zone 1 shows no apparent intensity fluctuation whereas Zone 4 shows strong focusing/defocusing phenomena.

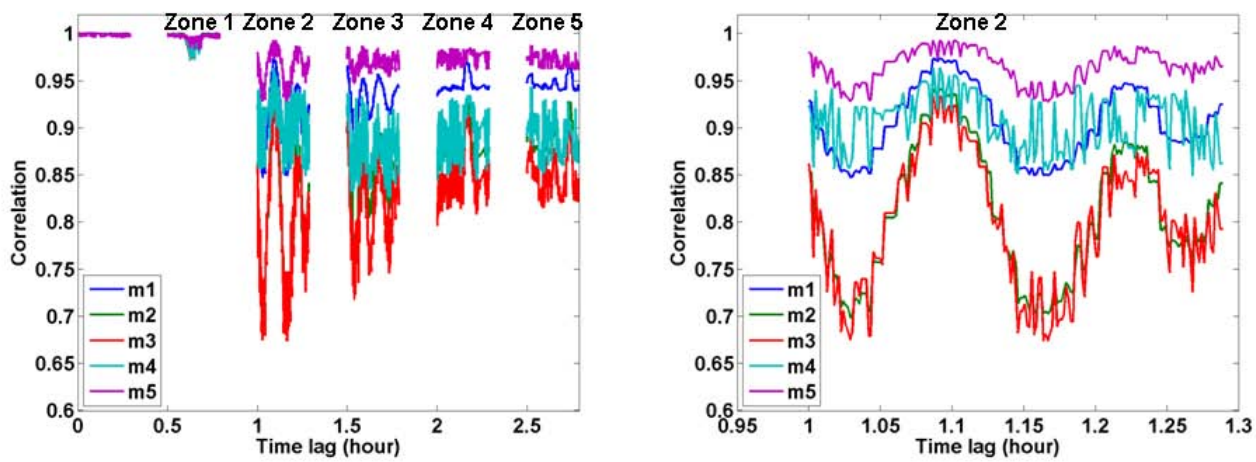

Figure 3: Normalized mode correlation coefficients of signals from a moving source (R/V Sharp). Reference time = Aug 17, 2006 20:40, frequency = 150Hz.

B. High Frequency Acoustics - KAM08 Experiment

During the KAM08 experiment, acoustic transmissions were made between a moving source (ship-based) and a moored receiving array. The water column depth at the receiving array was about 100 m, while the water column depth at the source varied from 50-500 m with varying bathymetry. Chirp transmissions were made with a center frequency of 16 kHz, while the receiving array sampled at 50 kHz. Figure 4 shows plots of three transmissions as examples of these data. Upper panels are bathymetry and source-receiver positions and lower panels are the respective channel responses. Transmission distance, site bathymetry, and surface roughness were the primary factors influencing channel impulse response.

Both ray-based (Bellhop [9]) and parabolic equation (MMPE [10]) models are being calibrated for the experimental conditions, including moving source and rough surface. A Datawell waverider-DWRG recorded the power spectrum of the surface waves, averaged over 30 min. intervals [11]. Using these data, a statistically consistent surface is re-constructed. This surface is combined with bathymetry and thermistor string data to give an accurate environment for input to the models [8].

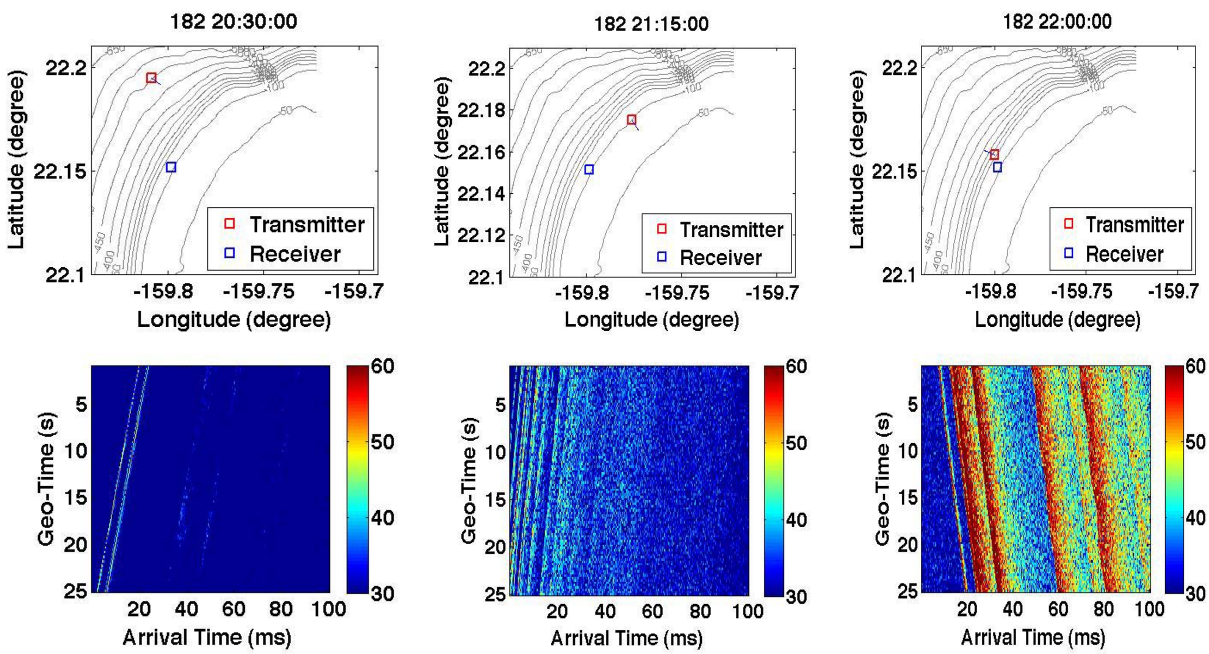

Figure 4: (a) Site geometry with source and receiver position as well as iso-bath lines. (b) Select transmissions with arrival time vs. geo-time.

C. Surface Wave Model

A model has been constructed for the generation of realistic surface waves [12]. The evolution equations for water surface fluctuation are given by

$$\eta_t + \nabla_h \phi^s . \nabla_h \eta - (1 + \nabla_h \eta . \nabla_h \eta) \left[\sum_{m=1}^{M} \sum_{k=0}^{M-m} \frac{\eta^k}{k!} \sum_{n=1}^{N} \phi_n^{(m)}(t) \frac{\partial^{k+1}}{\partial z^{k+1}} \Psi_n(\vec{x},0) \right] = 0 \qquad (1)$$

$$\phi_t^s + g\eta + \frac{1}{2} \nabla_h \phi^s . \nabla_h \phi^s - \frac{1}{2}(1 + \nabla_h \eta . \nabla_h \eta) \left[\sum_{m=1}^{M} \sum_{k=0}^{M-m} \frac{\eta^k}{k!} \sum_{n=1}^{N} \phi_n^{(m)}(t) \frac{\partial^{k+1}}{\partial z^{k+1}} \Psi_n(\vec{x},0) \right]^2 = -\frac{P_a}{\rho} \qquad (2)$$

where η is water surface fluctuation ϕ^s is surface velocity potential, $\nabla_h = (\partial / \partial x, \partial / \partial y)$ is horizontal gradient, P_a is atmospheric pressure, and ρ is density of the fluid. Following Dommermuth and Yue [13] we use a two-step procedure for solving Eqs. (1) and (2). First, all spatial derivatives in the evolution equations are found by a pseudospectral approach utilizing fast-Fourier and inverse fast-Fourier transforms between physical space and wavenumber space. All nonlinear products in the evolutions are calculated in physical space. Second, starting with given initial conditions for water surface fluctuation η and surface velocity potential ϕ, time integration is done with a fourth order Runge-Kutta time integrator. Starting from initial conditions, this two-step procedure is repeated for every time step. Figure 5(a) shows power spectrum data collected by a Datawell directional waverider buoy during KAM08, the corresponding snapshot of 2-D propagating waves with a principal direction from NE (Fig. 5b), and its1-D cross section in the direction of the acoustic track (Fig. 5c). The generated surface waves are being integrated as inputs to the 2-D and 3-D PE and ray-based acoustic models to account for sea surface roughness.

D. Instrumentation

Under an ONR DURIP project [14], we are developing an acoustic multiple-input/multiple-output (MIMO) transmission/acquisition system on the University of Delaware Gavia AUV [15]. The Gavia AUV is a modular, small size AUV (20 cm in diameter, 77 kg in air) in use by numerous NATO country naval forces that has a depth rating of 200 m. With advanced navigation systems such as GPS, DVL-aided Inertial Navigation System (INS) and satellite surface communication capabilities, it has been tested through various ocean missions. The MIMO transceiver system will be capable of simultaneous transmissions of up to four data streams as well as acoustic reception via eight hydrophones from a towed array. Figure 6 shows the components of this system: (A) A/D converter module and (B) Open (flooded) section with three transducers aboard the Gavia AUV shown in (C).

IMPACT/APPLICATIONS

The low frequency component of our research contributes to the understanding of sound propagation in complex shallow water regions. We have developed a theory to explain the temporal and spatial intensity fluctuations caused by internal solitons. The high frequency part of our research has impacts on the development of new underwater communications systems with more efficient decoding capabilities.

RELATED PROJECTS

In the low frequency band research, we have been working with Drs. J. Lynch at Woods Hole Oceanographic Institute (WHOI) and B. Katsnelson from University of Voronezh, Russia. For the research work in the high frequency band, we are collaborating with colleagues from Scripps Institution of Oceanography (Drs. W. Hodgkiss and H.-C. Song), Applied Physics Laboratory-University of Washington (Dr. D. Rouseff), Naval Post Graduate School (Dr. K. Smith), and Heat, Light, and Sound Research Inc. (Dr. M. Porter).

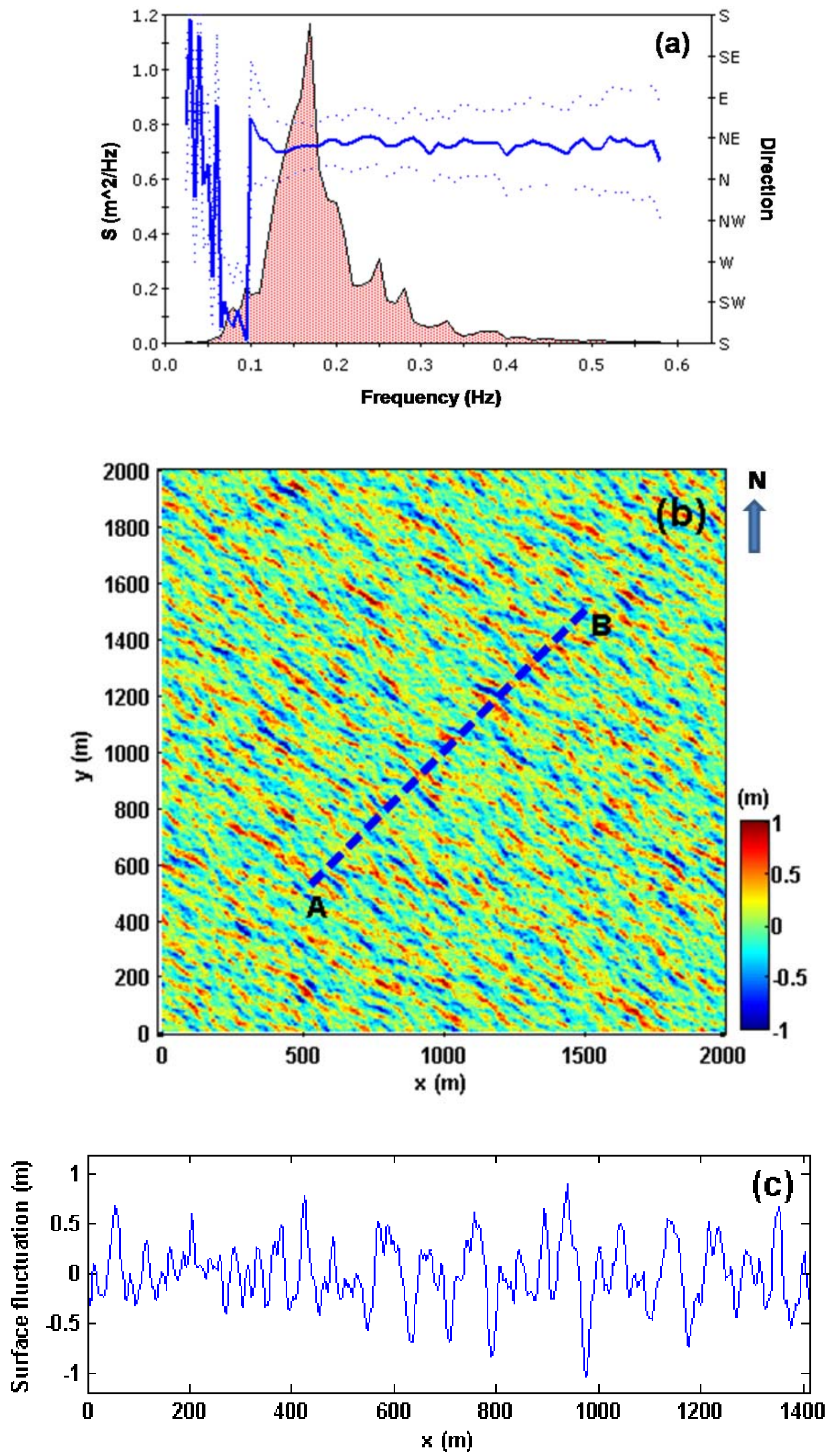

Figure 5:   (a) Power spectrum on 06-20-2008 at 20:12:00 GMT collected by a Datawell directional waverider buoy during KAM08 experiment; (b) Snapshot of a 2-D propagating linear waves with principal direction from NE corresponds to the spectrum shown in (a). Water depth is 100 m. Track A-B indicates the location of a 1-D cross section; (c) Snapshot of the 1-D cross section in the direction of acoustic track (A-B dashed line in(b)).

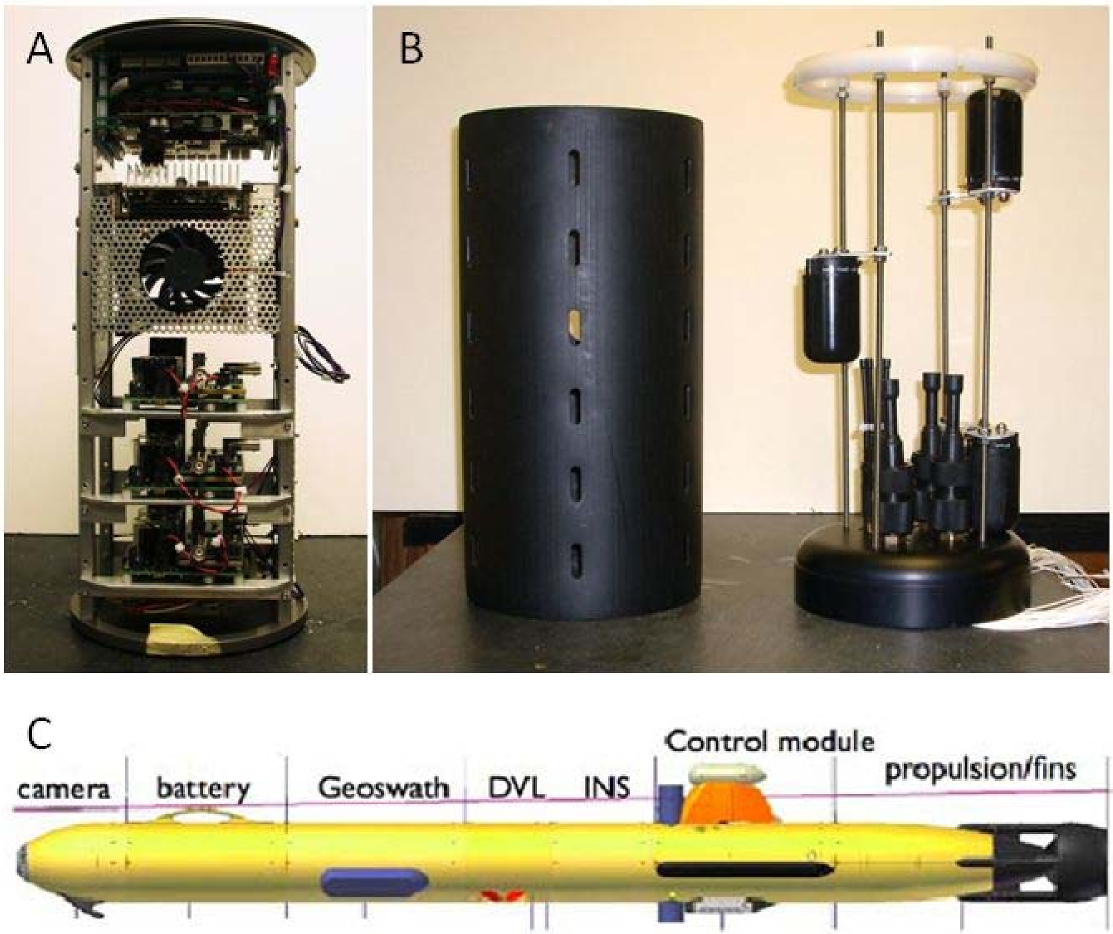

Figure 6: Gavia AUV and UDel MIMO Module. A) A/D converter module. B) Open (flooded) section with 3 transducers. C) Gavia AUV and general specifications: 2.7 m long, 20 cm diameter, 77 kg (weight in air), 200m depth rating, INS/DVL Navigation, side-scan sonar (900/1800 kHz), 2 mega-pixel color camera/strobe, Geoswath Inteferometric bathy sonar (500 kHz), W-Lan & Satellite Communication.

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